AD-A100 702 MOORE SCHOOL OF ELECTRICAL ENGINEERING PHILADELPHIA P--ETC F/G 12/1
FACTORS AFFECTING MEAN POWER RESPONSE TO MULTIPATH RAYS ARRIVIN--ETC(U)
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Fred Haber and Paul Yeh, "Factors Affecting Mean Power Response to Multipath Rays Arriving at Different Elevation Angles," and "Multi-beam Noise Correlation," VFRC QPR No. 32, February 1980.

FACTORS AFFECTING MEAN POWER RESPONSE TO MULTIPATH RAYS ARRIVING AT DIFFERENT ELEVATION ANGLES

The power response to a source along the main beam, assumed to be in the y-z plane, was given in QPR No. 31, equation (10), page 30, as

$$\langle |A^2(\tfrac{\pi}{2},\theta_s)|\rangle = \sum_{m=1}^{M} \langle B_m^2\rangle N\,\{1+(N-1)\cdot$$

$$e^{-[\sigma_y^2k^2(\sin\theta_m-\sin\theta_s)^2 + \sigma_z^2k^2(\cos\theta_m-\cos\theta_s)^2]}\}$$

where it was assumed that elements are distributed normally in dimensions x, y, z, with standard deviation σ_x, σ_y, and σ_z. θ_m are co-latitude angles of arrival of ray m, m=1,2,...M, and ray magnitude is B_m. The exponential factors determine the gain variation with element spread and focusing angle θ_s (measured with respect to the vertical). To better see how σ_y and σ_z affect the beam width in elevation calculations were made of the two factors

$$I_y(\theta_m, \theta_s) = e^{-\sigma_y^2k^2(\sin\theta_m-\sin\theta_s)^2}$$

and

$$I_z(\theta_m, \theta_s) = e^{-\sigma_z^2k^2(\cos\theta_m-\cos\theta_s)^2}$$

Figure 3.1 (a),(b),(c),(d),(e),(f) shows some representative results for I_y and I_z as a function of θ_m with θ_s a parameter, and Table I shows the half power beamwidth in elevation, denoted $\Delta\theta_m$ corresponding to each function. Note that when θ_s=90°, the array is focused along the y-axis and the mean beamwidth is symmetrical around the y-axis in the y-z plane. When θ_s is set to 80° or 85°, I_y is a bimodal function of θ_m with a local minimum at θ_n = 90°. The local minimum is sometimes shallow and sometimes quite deep. When I_y falls below 0.5 at θ_n = 90°, Table I lists the beamwidth of each hump; when I_y is above 0.5 at θ_n = 90°, the beamwidth given is the total range between half power points and runs from a point below the horizontal to a point above the horizontal. For instance, for σ_y = 20λ, σ_z = 4λ, θ_s = 85° the 0.5 power beamwidth determined by I_y ranges from 81.75° to 98.25°, a range of 16.5°.

As one might expect I_y does not equally strongly influence the beamwidth

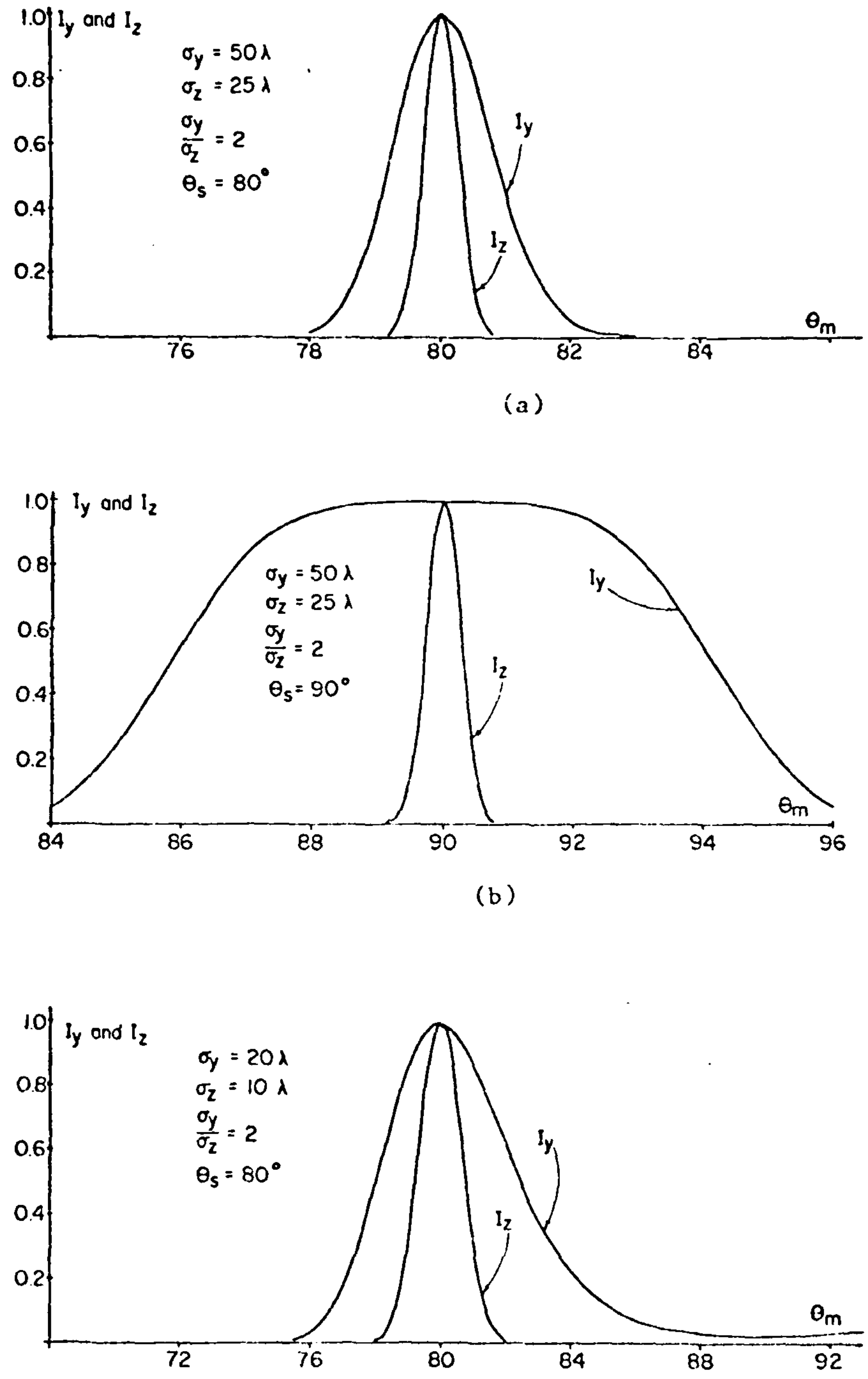
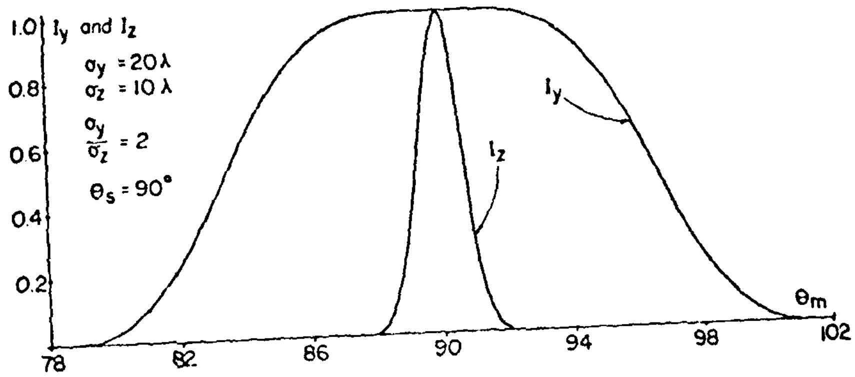
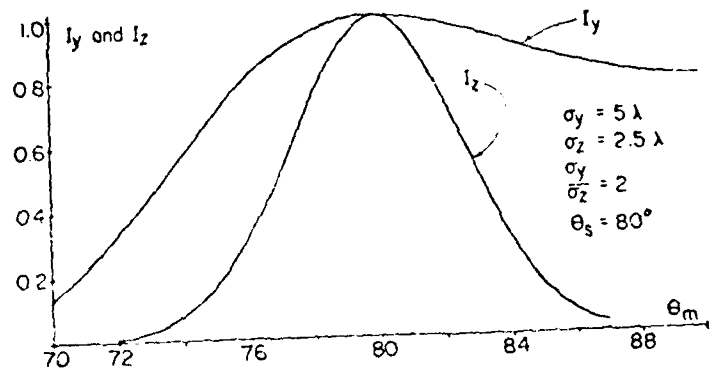


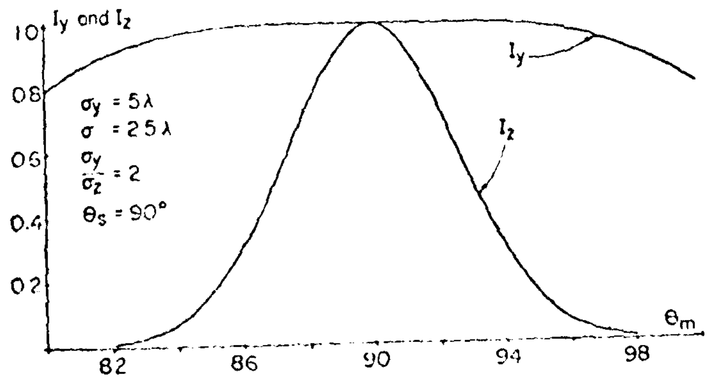
FIGURE 3.1. FACTORS I_y AND I_z DETERMINING VERTICAL BEAMWIDTH. (a,b,c)



(d)



(e)



(f)

FIGURE 3.1. FACTORS I_y AND I_z DETERMINING VERTICAL BEAMWIDTH. (d,e,f)

	θs	$\Delta\theta_m$ on I_z	$\Delta\theta_m$ on I_y
$\sigma_y = 5\lambda$, $\sigma_z = 2.5\lambda$	90°	6.1°	> 20.0°
	85°	6.1°	28.2°
	80°	6.1°	33.2°
$\sigma_y = 20$, $\sigma_z = 10\lambda$	90°	1.6°	13.2°
	85°	1.5°	16.6°
	80°	1.5°	4.5°
$\sigma_y = 50$, $\sigma_z = 25$	90°	0.6°	8.4°
	85°	0.6°	3.75°
	80°	0.6°	1.75°
$\sigma_y = 5\lambda$, $\sigma_z = \lambda$	90°	15.2°	> 20.0°
	85°	15.3°	> 20.0°
	80°	14.2°	> 20.0°
$\sigma_y = 20\lambda$, $\sigma_z = 4\lambda$	90°	3.8°	13.0°
	85°	3.8°	16.5°
	80	3.8°	4.5°
$\sigma_y = 50\lambda$, $\sigma_z = 10\lambda$	90°	1.5°	8.4°
	85°	1.5°	3.75°
	80°	1.5°	1.75°

TABLE I MEAN 1/2-POWER BEAMWIDTH, $\Delta\theta_m$, WITH NORMALLY DISTRIBUTED ELEMENT POSITIONS.

in elevation, though for $\sigma_y = 50\lambda$, $\sigma_z = 10\lambda$, and $\theta_z = 80°$ the two functions are nearly equal. As a rule with $\sigma_y/\sigma_z = 2$, I_z established the pattern in elevation and it is sufficient to consider it and to let $I_y = 1$.

In the work discussed below on the noise correlation we consider elements uniformly dispersed in depth where here we have assumed normally distributed elements. Extraordinary differences between these two cases are not expected though. Similar computations of the uniformly distributed case were therefore not carried out.

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Fred Haber

MULTIBEAM NOISE CORRELATION

Consider the system in Figure 3.2, QPR No. 31. The branch signal level, when the array is focused in the vertical plane containing the Y-axis and at an angle θ_{si} to the vertical, is given by (2) of QPR 31. The equation is rewritten here

$$A(\theta_{si}) = \sum_{m=1}^{M} \sum_{n=1}^{N} B_m e^{j\{ky_n(\sin\theta_m - \sin\theta_{si}) + kz_n(\cos\theta_m - \cos\theta_{si}) + \phi_m\}} \tag{1}$$

The complex weight

$$W_i = A_i\, e^{-j\psi_i \operatorname{sgn} f} \tag{2}$$

shown in the figure referred to is given by

$$W_i = A^*(\theta_{si}) \tag{3}$$

when noise levels into all the branches have equal mean square value and are independent from branch to branch. The total system signal output is, in this case,

$$W = \sum_{i=1}^{I} A(\theta_{si})\, W_i = \sum_{i=1}^{I} |A^2(\theta_{si})| = \sum_{i=1}^{I} A_i^2 \tag{4}$$

and the total noise ouput has a mean square value given by the second expression p. 35 of QPR 31, namely,

$$\langle N^2(t)\rangle = \sum_{n=1}^{N} \langle n_n^2(t)\rangle \sum_{i=1}^{I} \sum_{j=1}^{I} \langle A_i A_j \cos(\phi_{ni} - \phi_{nj} + \psi_i - \psi_j)\rangle \tag{5}$$

where the A_i are defined by (2). The angles in (5) are given by the following

$$\phi_{ni} = -k[y_n \sin\theta_{si} + z_n \cos\theta_{si}] \tag{6}$$

$$\psi_i = \tan^{-1} \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} B_m \sin[\phi_{ni} + \hat{\phi}_{nm} + \phi_m]}{\sum_{m=1}^{M} \sum_{n=1}^{N} B_m \cos[\phi_{ni} + \hat{\phi}_{nm} + \phi_m]} \tag{7}$$

where we have used (1) and (6) in writing (7) and where we have denoted

$$\hat{\phi}_{nm} = k(y_n \sin\theta_m + z_n \cos\theta_m) \tag{8}$$

If the noise processes in the different branches were uncorrelated the output mean square noise level would be

$$\langle N^2(t)\rangle = \sum_{n=1}^{N} \langle n_n^2(t)\rangle \sum_{i=1}^{I} \langle A_i^2\rangle \tag{9}$$

The output signal-to-noise ratio (SNR) is here defined by

$$\gamma = \frac{\langle W^2\rangle}{2\langle N^2(t)\rangle} = \frac{\left(\sum_{i=1}^{I} A_i^2\right)^2}{2N\langle n_n^2(t)\rangle \sum_{i=1}^{I} \langle A_i^2\rangle} \tag{10}$$

where we have assumed mean noise power at all elements to be equal and where we have used (2), (3), (4) and (9) to write (10). If the A_i were not random variables (or if they were to have small variance), γ would be the sum of SNR's of the branches, a result well known for maximal ratio combining of diversity branches in communications. In our situation the branch noises may not be uncorrelated and there is the possibility of larger noise levels. We examine conditions which will give uncorrelated noises. (5) can be expanded to give

$$\langle N^2(t)\rangle = \sum_{n=1}^{N} \langle n_n^2(t)\rangle \sum_{i=1}^{I} \sum_{j=1}^{I} \langle A_iA_j \cos(\phi_{ni}-\phi_{nj})\cos(\psi_i-\psi_j) - A_iA_j \sin(\phi_{ni}-\phi_{nj})\sin(\psi_i-\psi_j)\rangle \tag{11}$$

A_i and ψ_i are the amplitude and phase of the complex amplitude on branch i as given by (1). These random variables are not determined by the position random variables y_n and z_n because of the presence of ϕ_n in the exponent of (1) which is uniformly distributed in (0, 2π). On the other hand, the ϕ_{ni} are determined only by the position random variables y_n and z_n. Thus the pair (A_i, ψ_i) are independent of ϕ_{ni} for all i. Furthermore from (6) we see that ϕ_{ni} is a linear function of the random variables y_n and z_n. We assume the latter to be symmetrically distributed around zero so that $\langle \sin(\phi_{ni}-\phi_{nj})\rangle = 0$. (11) thus reduces to

$$< N^2(t) > = \sum_{n=1}^{N} < n_n^2(t) > \sum_{i=1}^{I} \sum_{j=1}^{I} < A_i A_j \cos(\psi_i - \psi_j) > < \cos(\phi_{ni} - \phi_{nj}) > \quad (12)$$

We point out that if either $< \cos(\phi_{ni} - \phi_{nj}) >$ or $< A_i A_j \cos(\psi_i - \psi_j) >$ is zero for all $i \neq j$ (12) reduces to (9) that is, the uncorrelated branch noise case is obtained. We investigate

$$< \cos(\phi_{ni} - \phi_{nj}) > = < \cos k[y_n(\sin \theta_{si} - \sin \theta_{sj}) + z_n(\cos \theta_{si} - \cos \theta_{sj})] > \quad (13)$$

since it is much less complicated than $< \cos(\psi_i - \psi_j) >$. The angles θ_{si} of interest to us are in the range of about 80° to 100°. It can be demonstrated that $(\sin \theta_{si} - \sin \theta_{sj}) << (\cos \theta_{si} - \cos \theta_{sj})$ for angles in this range. Also, if we are to have high vertical resolution, the variance of z_n will have to be of the same order as the variance of y_n. Thus we can argue that (13) can be approximated by

$$<\cos(\phi_{ni}-\phi_{nj})> \doteq <\cos k\, z_n(\cos \theta_{si} - \cos \theta_{sj})> \quad (14)$$

so that (12) becomes

$$< N^2(t) > = \sum_{M=1}^{N} < n_n^2 > \sum_{i=1}^{I} \sum_{j=1}^{I} < A_i A_j \cos(\psi_i - \psi_j) > \quad (15)$$

$$\cdot < \cos kz_n(\cos \phi_{si} - \cos \phi_{sj}) >$$

If the rv z_n is here assumed uniformly distributed in a range (-h,h) then the rv $(\phi_{ni} - \phi_{nj})$ will be correspondingly uniformly distributed in a range $(-a_{ij}, a_{ij})$. We therefore have

$$< \cos(\phi_{ni} - \phi_{nj}) > = \frac{\sin a_{ij}}{a_{ij}} \quad (16)$$

where

$$a_{ij} = kh(\cos \theta_{si} - \cos \theta_{sj}) \quad (17)$$

(16) suggests that to make $< \cos(\phi_{ni}-\phi_{nj}) > = 0$ for $i \neq j$, branch focii be placed so that $a_{ij} = m\pi$, m an integer.

The θ_{si} will all be concentrated around 90°, generally in the range (80°, 100°). Thus we are led to write

$$\hat{\theta}_{si} = \theta_{si} - 90°$$

so that

$$\cos\theta_{si} = -\sin\hat{\theta}_{si} \doteq -\hat{\theta}_{si}$$

and using (17)

$$a_{ij} \doteq kh\,(\theta_{sj}-\theta_{si}) \tag{18}$$

The angular separation between beams to get uncorrelated noise outputs at the different branches should therefore be

$$\theta_{sj} - \theta_{si} = \frac{m\pi}{kh}$$

If, for instance, $h = 25\lambda$ (meaning that the array size in depth is 50 wavelengths which at Hz implies a depth of about 750 meters) adjacent beams ought to be spaced

$$\Delta\theta_s = \frac{\pi}{kh} = 1/50 \text{ rad} \doteq 1.15°$$

in order for the noise variables entering into the final summer to be uncorrelated.

The next step to be taken will be to determine the array power response with array output processed as described above. If the multipath rays were to come in on the center lines of the vertically spread beams the overall array response would be maximized. Some beams are expected however to see no incoming rays, others may see more than one ray. In the latter case the multipath is not resolved by the array processor and the combined rays add non-coherently. The corresponding diversity branch will see a fluctuating level depending on the relative ray phases. While the processor cannot improve the signal level in this case the weighting circuit will take account of this fluctuation to maximize the signal to noise ratio by suppressing the branch output if the signal component is small and amplifying the branch output if the signal component is large.

The calculation of these effects is time consuming. We plan to carry out a simulation of this next step by assuming a fixed number of rays arriving, each uniformly distributed over a range of latitude angles about ±10% relative to the horizontal. Independent noise at each sensor will be assumed. Beams will be spaced as specified above covering the same range of latitudes and the statistical properties of the array output SNR will be found. This calculation will also serve as a test of assumptions made earlier to simplify calculations of noise output.

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--       SONOBUOY    ,(U)  PASSIVE SONAR     ,
--  37 - DESCRIPTORS:     (U)  DISTRIBUTION,(U)  GAIN  ,(U)  PASSIVE SONAR     ,
--       (U)  SONOBUOYS   ,(U)  UNDERWATER SOUND  ,(U)  ACOUSTIC COMPATIBILITY  ,
--       (U) *UNDERWATER ACOUSTICS    ,(U) *ACOUSTIC ARRAYS   ,(U) *ACOUSTIC
--       DETECTION,(U)  ACOUSTIC TRACKING ,(U)  EFFECTIVENESS      ,(U)

--       ELECTROMAGNETIC COMPATIBILITY ,
--  23 - TECHNICAL OBJECTIVE:   (U)  TO DEVELOP TECHNIQUES IN SIGNAL ANALYAIA
--       TO MAXIMIZE ACHIEVABLE ARRAY GAIN OF A RANDOM SONOBUOY ARRAY.
--  24 - APPROACH:  (U)  INVESTIGATE PHASE DECORRELATION EFFECT ON ARRAY GAIN
--       AND WAYS TO OVERCOME THESE EFFECTS
--  25 - PROGRESS:  (U)  EARLIER WORK FOCUSED ON METHODS OF LOCALIZING ELEMENTS
--       OF A RANDOM ARRAY  THEORY HAS BEEN DEVELOPED. VALLEY FORGE RESEARCH
--       CENTER QUARTERLY PROGRESS REPORT, FEB. 1979 (U).
--  13 - WORK UNIT START DATE:  MAR 77
--  14 - ESTIMATED COMPLETION DATE:       CD
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-- 11 - TITLE: (U) RESEARCH IN DISTRIBUTED ARRAYS
-- 1 - AGENCY ACCESSION NO: DN775290
-- 2 - DATE OF SUMMARY: 12 NOV 80
-- 39 - PROCESSING DATE (RANGE): 30 NOV 80
-- 6 - SECURITY OF WORK: UNCLASSIFIED
-- 12 - S + T AREAS:
-- 000200 ACOUSTICS
-- 000100 ACOUSTIC DETECTION
-- 21E - MILITARY/CIVILIAN APPLICATIONS: MILITARY
--10A1 - PRIMARY PROGRAM ELEMENT: 62711N
--10A2 - PRIMARY PROJECT NUMBER: F11121
--10A2A - PRIMARY PROJECT AGENCY AND PROGRAM: F11121
--10A3 - PRIMARY TASK AREA: RF11121810
--10A4 - WORK UNIT NUMBER: NR-129-102
--17A1 - CONTRACT/GRANT EFFECTIVE DATE: MAR 77
--17A2 - CONTRACT/GRANT EXPIRATION DATE: FEB 80
-- 17B - CONTRACT/GRANT NUMBER: N00014-77-C-0252
-- 17C - CONTRACT TYPE: COST TYPE
--17D2 - CONTRACT/GRANT AMOUNT: $ 25,000
-- 17E - KIND OF AWARD: EXT
-- 17F - CONTRACT/GRANT CUMULATIVE DOLLAR TOTAL: $ 130,000
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